

Spacecraft-to-Earth Communications for Juno and Mars Science Laboratory Critical Events

Melissa Soriano, Susan Finley, Andre Jongeling, David Fort, Charles Goodhart, David Rogstad, Robert Navarro
 Jet Propulsion Laboratory
 California Institute of Technology
 Pasadena, CA 91109
 818-393-7632
 Melissa.A.Soriano@jpl.nasa.gov

Abstract— This paper describes the Entry, Descent, and Landing (EDL) Data Analysis (EDA) system. The EDA software supports the real-time interpretation of Multiple Frequency-Shift Keying tones provided by the spacecraft. The objective of this software is to provide communication of status between the spacecraft and the mission personnel on Earth during critical events when low rate telemetry is not possible. Although these communications cannot be used to affect the landing due to the length of time required at these distances, this information is important in the case of a mission failure. Mars Science Laboratory (MSL) will utilize the EDA software during EDL. Juno usage will include deep space maneuvers, Jupiter orbital insertion, and its period reduction maneuver. Results are presented from the Juno tones test. Simulated MSL and Juno signals were also generated and these results are analyzed.

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1. INTRODUCTION

There are four EDA systems: two for Juno cruise and orbit insertion support and two for MSL EDL support. This redundancy allows for simultaneous support of both missions if needed. All of the EDA systems are physically located in JPL's Radio Science Operations Room at Space Flight Operations Facility (SFOF).

The spacecraft signals are first received by the Deep Space Network 70-m and 34-m antennas and recorded by Radio Science Receivers. The Radio Science Receiver (RSR) is an open-loop receiver that digitizes, filters, and downconverts the signal about predicted center frequencies into narrow channels. In this case, a 100 kHz, 16-bit complex subchannel is used. The EDA systems are located

on the flight operations network, which provides a direct connection to the RSRs at the Deep Space Communications Complexes (DSCC) where the spacecraft signals are recorded. Local JPL operators configure and run the EDA systems. Spacecraft tones representing discrete events are processed in real-time. Plots and a tone summary table are provided in real-time to the Mission Support Area (MSA) at SFOF. An overview of the EDA system within the Deep Space Network is shown in Figure 1.

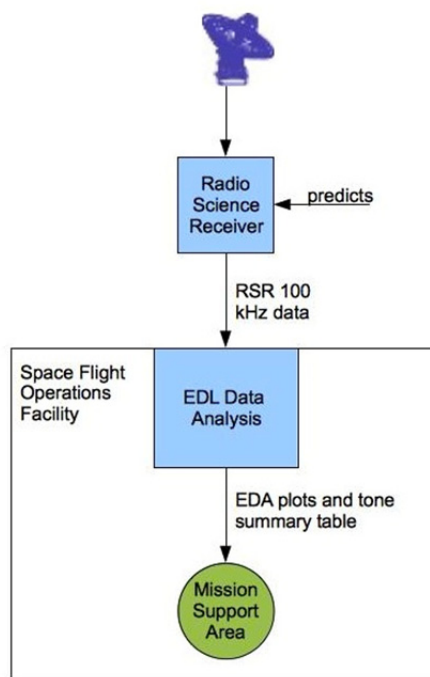


Figure 1- Overview of EDA system within Deep Space Network

2. SYSTEM DESIGN

Each signal consists of a carrier and one of many sub-carriers. The transmitted carrier frequency remains constant while the sub-carrier frequencies shift to convey information. Tone detection is accomplished using a Fast Fourier Transform (FFT)-based frequency and frequency rate loop on the carrier.

Each experiment is divided into time segments with different signal dynamics. An example sequence of

segments is: cruise, entry, parachute deployment, bridle deployment, landing. Each segment consists of a series of states, each of which may have unique processing parameters, including the number of samples per FFT, the number of seconds per integration, and the range of frequencies, frequency rates, and frequency accelerations to search. During initial signal acquisition, a large range of frequencies and frequency rates and short FFTs are used to search for the signal. Once a signal is detected, the software tracks it utilizing a narrowed range of frequencies and frequency rates as well as longer FFTs. This strategy allows the EDA software to track signals with high dynamics and Signal to Noise Ratios as low as 11 dB-Hz [10]. If the signal drops below the specified threshold signal-to-noise-ratio (SNR) for the current state, the EDA shifts to the previous state, which utilizes different signal processing parameters.

During the period of highest dynamics, the signal may be lost. If this occurs, the software can reacquire the signal and process the data backwards in time in order to recover as much data as possible. As the data is processed, a tone summary table is produced that describes all received tones and their characteristics, as well as plots of residual carrier frequency, actual and predicted frequency, frequency rate, frequency acceleration, and carrier signal-to-noise ratio.

The EDA software is designed to be multi-threaded, with separate threads to track the signal, backtrack (if the signal was lost), and refine digital signal processing. For the Mars Exploration Rovers (MER) and Cassini, the EDA system utilized a Sun workstation for user displays and a Linux-based cluster of eight nodes for signal processing of the data. For MSL and Juno, the EDA software was ported to a single Linux workstation with dual six-core processors. The new EDA system provides improved performance using newer hardware with a smaller footprint.

EDA Software Processes

The EDA software was originally developed for and utilized by the Mars Exploration Rovers [11]. The software includes several real-time processes for retrieving the data records, processing them, displaying the results, and providing an interface for the operator.

Distributed Data Service (DDS) is responsible for retrieving data records in real-time from the specified RSR. DDS reads the header of each record and determines the sample rate and number of bits per sample in the data. I and Q values are extracted from each record and written to the local EDA disk.

Operate (OPR) is the main interface to the EDA operator. The operator must specify a configuration file that controls the system and includes key signal processing parameters such as the RSR filename, FFT frequency resolution, and frequency search range. OPR also controls the overall state of the system, which may be unconfigured, configured, or

running. OPR also accepts a series of commands which can be used to adjust or override the EDA configuration in real-time. Only one OPR process may run at a time.

Process (PRC) is responsible for the main data processing and for distributing this process to the cluster sub-processes. The term “cluster” remains from when each of these processes existed on a separate computer in the MER EDA system. In the new EDA system, each cluster sub-process runs on its own processor core. PRC distributes the FFT calculations for acquiring, tracking, and (if needed) backtracking the carrier and tones to the cluster subprocesses and collects results.

Display (DSP) provides displays of plots and the tone summary table to the users. Multiple instances of DSP may run at once. In normal operation, the EDA operator runs an instance of DSP and mission support personnel in the Mission Support Area run other instances. Each DSP may utilize its own plot window parameters.

System Specifications

The EDA systems are Dell PowerEdge T710 tower servers. Each system features Dual Intel Xeon X5660 (six-core) processors at 2.8 GHz, 48 GB of memory, and a RAID-5 configuration with 3 250 GB drives. These systems were selected based on benchmarking and on the performance of the previous EDA systems utilized by MER. Each system utilizes 32-bit Linux Debian as its operating system. The decision to use a 32-bit operating system facilitated the porting of the previous software to the current EDA system.

3. JUNO

The Juno spacecraft was launched from Cape Canaveral Air Force Station in Florida on August 5, 2011. The goal of the Juno Mission is to understand the origin and evolution of Jupiter. The spacecraft is a solar powered spinning orbiter [1]. Cruise time to Jupiter is about 5 years. The spacecraft uses an Earth-Gravity-Assist trajectory that provides additional energy for reaching Jupiter [2]. This trajectory relies on deep space maneuvers about a year after launch. During maneuvers such as these when the main engine burns, the more powerful high gain antenna will be pointed away from Earth, so the toroidal low gain antenna (TLGA) must be used to communicate information in the form of tones to Earth [3].

The Juno mission includes the following usage of communication tones: the tones test, two deep space maneuvers (DSM), Jupiter Orbit Insertion (JOI), and the Period Reduction Maneuver (PRM). The dates of these events are shown in **Table 1**. In preparation for usage during critical maneuvers, a tones test took place on September 7, 2011. The carrier is at 8.404 GHz (X-band) with phase modulation of a square wave subcarrier.

Table 1- Planned dates of Juno EDA Usage

Event	Date
Tones Tests	September 7, 2011
Deep Space Maneuvers	September 2012
Jupiter Orbit Insertion	July 4-5, 2016
Period Reduction Maneuver	October/November 2016

4. MARS SCIENCE LABORATORY

The Mars Science Laboratory spacecraft was launched on November 26, 2011 from Cape Canaveral Air Force Station. The landing site on Mars will be Gale Crater. The spacecraft is composed of a cruise stage, descent stage, entry aeroshell, and rover [4]. The aeroshell is composed of a heat shield and a backshell. MSL will maintain several forms of communication with Earth during Entry, Decent, and Landing (EDL). Direct to Earth (DTE) communications will take place using the X-band low gain antennas. Relay communications to Mars Reconnaissance Orbiter will utilize the UHF antennas and will have an expected bandwidth of 8 kbps [4]. During entry into the atmosphere, charged particles in the plasma surrounding the spacecraft will reflect and absorb signals. This attenuation occurs only above critical electron number density, which depends on the frequency of the communications link. Critical electron density is 8.8×10^{11} particles/cm³ at an X-band frequency of 8.4 GHz and 2.0×10^9 and a UHF frequency of 0.4 GHz. Simulations of electron densities during EDL indicate that MSL is likely to experience a UHF communication blackout of up to ~95 seconds [5].

Entry, Decent, and Landing Overview

For the purposes of the EDA, the EDL sequence is composed of the following segments: EDL Start, Exo-Atmospheric, Entry, Parachute Descent, and Powered Descent [4]. The total duration of EDL from the beginning of EDL Start to touchdown is about 22 minutes. The EDL Start segment begins 15 minutes before entry. Tones start being transmitted approximately 11 minutes before entry using the Parachute Low Gain Antenna (PLGA) [8]. The separation of the cruise stage begins the Exo-Atmospheric segment. The cruise ballast mass separates and at this time DTE communications switches to the Tilted Low Gain Antenna (TLGA). Entry is defined at a radius of 3522.2 km from the center of Mars [4]. During entry, peak heating and deceleration take place, as well as regions of high Doppler dynamics. When the spacecraft reaches a specified navigated velocity, the parachute is deployed and the Parachute Descent segment begins. Communication

switches back to the PLGA [8]. The spacecraft experiences a rapid deceleration from over 450 m/s to approximately 100 m/s and heat shield also separates [4]. Parachute swinging is expected during this segment and may cause communication outages. When a specified altitude and velocity are reached, the backshell separates and the propulsion system initiates powered descent. DTE communication switches to the Descent Low Gain Antenna (DLGA) [8]. During the powered descent segment, there are periods of constant velocity and constant deceleration.

Based on the Gale Crater launch site, the launch window, and the spacecraft trajectory, the Earth will be occulted during landing. This loss of DTE coverage will begin approximately 313 seconds after entry, during the powered descent segment [7]. Tones will continue to be transmitted until touchdown but will not be possible to receive through DTE communication [8].

MSL tones are numbered 0 to 255 and tone n has a frequency of $\pm 2000 + n \cdot 70.5883$ Hz relative to the carrier. MSL plans to use different tone number meanings for each segment.

5. JUNO TONES TESTS

The Juno Tones tests took place on September 7, 2011, day of year (DOY) 250. The objective of the Juno Tones tests was to verify proper end-to-end data flow for tones, including processing and display of the tones by the EDA [6]. The tests were performed with the spacecraft in flight, and both spacecraft and ground systems configured as they will be during critical maneuvers. There was no telemetry or command modulation [6].

Juno tones have either a high or low priority. Both types of tones have a queue of length 1. High priority tones are always emitted for at least three seconds. Low priority tones are emitted for at least three seconds unless they are interrupted by a high priority tone. New tones are considered more valuable. If a tone is in the queue waiting to be sent and a new tone with the same priority is requested, the older tone is discarded in favor of the newer one. The Juno Tones Manager software is responsible for receiving tones requests from different subsystems, keeping track of both queues, and ultimately commanding emission of the tones.

A Tones Test sequence was developed to test the capabilities of the EDA. This sequence included 4 test cases: basic tones, prioritization, sustained sequence, and flurry of tones. The basic tones case exercised a range of tones from 0 to 511 and tones with adjacent frequencies, each emitted for 60 seconds. This case tested basic tones functionality. The prioritization case included both high and low priority tones in rapid succession. This case was designed to test prioritization, including the ability of a high priority tone to interrupt a low priority tone. The sustained test case was composed of ten tones, each emitted for 3

seconds. The flurry of tones test case included a mix of high and low tones with 1-2 second spacing [6].

During the Juno Tones tests, Radio Science Receivers (RSR) recorded 1-way X-band RCP and X-band LCP using 100 kHz 8 bit channels. Three tests took place, one with just DSS-14, one with DSS-14 and DSS-43, and one with just DSS-43. We will refer to these tests as a, b, and c, respectively. DSS-14 and 43 are both 70-meter antennas. Each RCP recording was processed by an EDA system using 1-second and 3-second integrations. The RSR and EDA systems are listed in **Table 2**. The duration of each tones test was about 12.5 minutes.

Table 2- Systems used in Juno Tones Test

Time (UTC)	RSR/WVSR	Data Filename	EDA
1530-1600	rsr1.gdscc	juno tata 14r	eda2
1530-1600	rsr1.gdscc	juno tata 14l	eda4
1700-1730	rsr1.gdscc	juno tatb 14r	eda2
1700-1730	rsr2.cdsc	juno tatb 43r	eda4
1700-1730	rsr1.gdscc	juno tatb 14l	eda2
1700-1730	rsr2.cdsc	juno tatb 43l	eda4
1830-1900	rsr2.cdsc	juno tate 43r	eda4
1830-1900	rsr2.cdsc	juno tate 43l	eda2
1830-1900	wvsr1.cdsc	250c-43r	eda2

Using a 100 kHz channel, 8 bits samples (each for I and Q), and a 260-byte header, the RSR data is 200260 bytes/record. A minimum bandwidth of about 1.6 Mbps is needed from the RSRs at the DSCCs to the EDAs at SFOF for real-time data transfer.

Actual Juno tones are numbered 0 to 180 and tone n has a frequency of $\pm 2000.9279 + n \cdot 40.769577$ Hz relative to the carrier. Key signal processing parameters specified in the EDA configuration file are shown in Table 3.

Table 3- Juno Nominal EDL signal processing parameters and search ranges

Parameter	1 second integrations	3 second integrations
FFT frequency resolution	1 Hz $N_{\text{FFT}} = 100,000$	1 Hz $N_{\text{FFT}} = 100,000$
Frequency search range	-200 Hz to 200 Hz (tracking) -20 Hz to 20 Hz (acquisition)	-200 Hz to 200 Hz (tracking) -20 Hz to 20 Hz (acquisition)
Pre-FFT frequency rate resolution	1 Hz/s	1 Hz/s
Pre-FFT frequency rate search range	-7 Hz/s to 7 Hz/s	-7 Hz/s to 7 Hz/s
Post-FFT frequency rate resolution	0.2 Hz/s	0.2 Hz/s
Post-FFT frequency rate search range	-0.8 Hz/s to 1.0 Hz/s	-0.8 Hz/s to 1.0 Hz/s
Threshold SNR	30 dB-Hz	25 dB-Hz
Detection interval, T, used in tracking/acquisition	1 second	3 seconds

All expected tones were detected, correctly identified, and interpreted by the EDA systems with 1-second integrations. The EDA systems produce several plots, including Carrier Frequency, Carrier Frequency Rate, Carrier Frequency Acceleration, Carrier Power, Sub-Carrier Power, Sub-Carrier Tones, and Actual and Predicted Sky Frequency. A Tone Summary table is also generated. Representative plots from the second test using DSS-14 are shown.

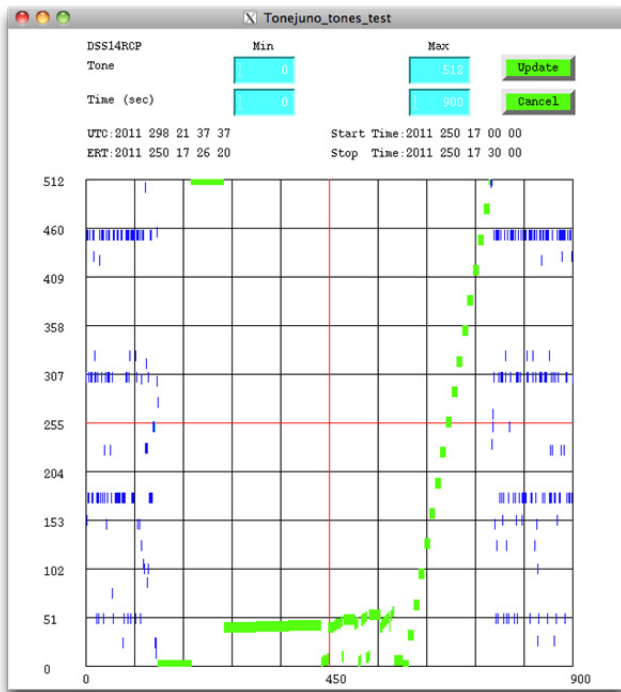


Figure 2- Tones for DOY 250, Test b using DSS-14

Tone numbers with respect to time (in seconds from the beginning of the recording) are shown in Figure 2. At each point, if the sub-carrier Signal-to-Noise-Ratio (SNR) is higher than the detection limit by a certain threshold, the point is colored green. All other points are colored blue. As shown in Figure 2, the sub-carrier SNR was higher than the threshold SNR throughout this test. This was the case for all of the Juno Tones tests.

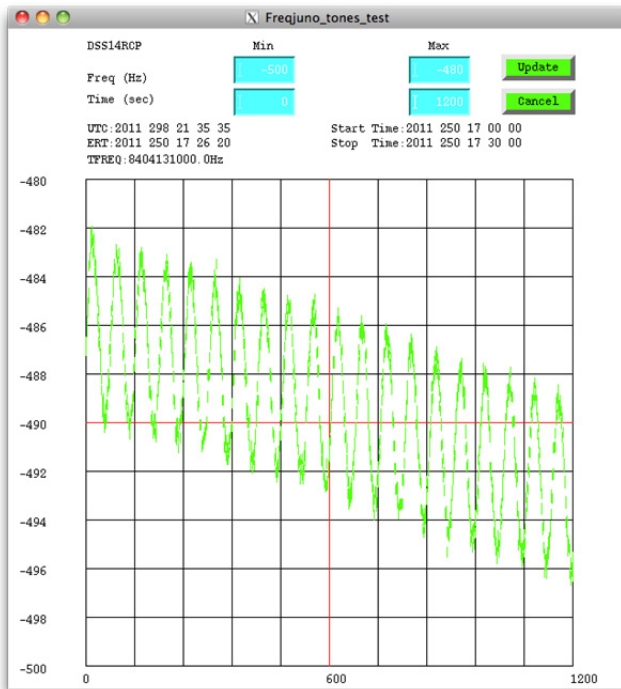


Figure 3- Carrier Frequency for DOY 250, Test b using DSS-14

Carrier residual frequency (in Hz) with respect to time (in seconds) is shown in Figure 3. On the day of the Juno Tones test, the spacecraft was spinning at about 1 rpm, with an Off-Earth angle of about 90 degrees [6]. A cyclic variation in the frequency with a period of approximately 60 seconds and peak-to-peak amplitude of about 7 Hz was observed. This effect is consistent with a Doppler effect due to the rotation of the TLGA around the spacecraft Z-axis as the spacecraft spins [6]. The spacecraft will be spinning at about 5 rpm during JOI.

Carrier SNR (in dB-Hz) with respect to time (in seconds) is shown in Figure 4. The green color indicates that the sub-carrier SNR was higher than the threshold SNR throughout this test. Using one-second integrations all tones measured Pc/No greater than the threshold Pc/No of 30 dB/Hz. Using three-second integrations all tones measured Pc/No greater than the threshold Pc/No of 25 dB/Hz. Predicted Pc/No from Radio Science for this day and time was approximately 50 dB-Hz, which is consistent with measured values from the EDA. Predicted Pc/No for Juno during JOI is between 12-15 dB-Hz. The value depends on the exact angle of the spacecraft Z-axis relative to Earth, which will be between 80 and 110 degrees.

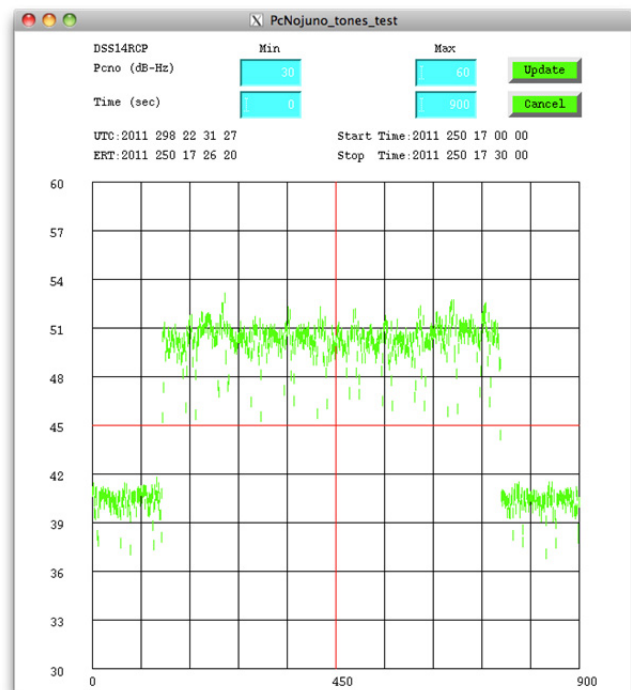


Figure 4- Carrier Signal-to-Noise-Ratio (dB-Hz)

The Juno Tones Manager software has a one second execution cycle for processing tones that was not synchronized with the executing Tones Test Sequence. For this reason, the tones that were actually emitted during each test varied slightly. Actual tone durations were determined by analyzing the spacecraft fault history table. Detected tone durations differed from actual tone durations by at most

one second. The number of tone durations that differed from the expected duration by one second for each test are shown in **Table 4**. The differences between actual and detected durations are caused by a lack of synchronization between times when tones are received and the one-second RSR records. Two tones may be received within a one-second record, resulting in ambiguities of up to one second.

Table 4- Number of tone durations that differed from expected durations by 1 second

Test	1 second integration	3 second integration
a, DSS-14	11	18
b, DSS-14	1	11
b, DSS-43	1	9
c, DSS-43	2	9

Two low priority tones that were emitted for one second were missed with three-second integrations (Test a, tone 3 during the flurry of tones test case and Test b, tone 10 during the sustained sequence test case). One advantage of longer integrations is that signals with lower SNR are more likely to be detected. However, a disadvantage is that two one-second tones may occur within a three second window and only the tone with the highest peak power will be detected.

6. CONCLUSIONS

Direct-to-Earth communications with Juno during Jupiter orbit insertion and Mars Science Laboratory during Entry, Descent, and Landing (EDL) will utilize Multiple Frequency Shift Keying tones. At these times, high dynamics and low SNR make communication especially challenging. The EDL Data Analysis system interprets these tones in real-time and provide status information about the spacecraft to Mission personnel.

An earlier version of the EDA system was used to successfully track the Mars Exploration Rovers during their entry, decent and landing. A new version of this system was built utilizing one computer with multiple cores instead of a cluster of single core machines and the software was updated and ported to this new hardware. The updated EDA system was demonstrated and tested in-flight during the Juno tones tests. All expected tones were detected, correctly identified, and interpreted by the EDA systems with one-second integrations.

7. ACKNOWLEDGEMENTS

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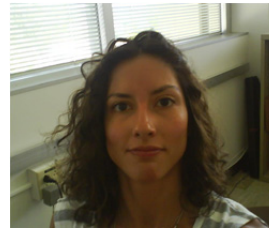
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BIOGRAPHIES



Melissa Soriano is a staff software engineer in the Tracking Systems and Applications Section at the Jet Propulsion Laboratory. She has developed real-time software for the Long Wavelength Array, NASA's Breadboard Array, and the Wideband VLBI Science Receiver used in the Deep Space Network. Melissa was also responsible for porting the EDA system from a Sun workstation and Linux cluster to a single Linux workstation with multiple cores. She has a BS from Caltech, double major in Electrical and Computer Engineering and Business Economics and Management. She also has an MS from George Mason University.



Susan Finley is a key staff member in the Processor Systems Development Group at JPL. She is the subsystem engineer for the Full Spectrum Processor subsystem deployed in NASA's Deep Space Network. Her experience includes the operation of the EDA for both of the MER landings on Mars as well as the operation of the Radio Science Receiver for the landing of the Huygens Probe on Titan and for the Phoenix landing on Mars.



Andre Jongeling joined JPL in 1991 where he is currently the Deputy Manager of the Communications Ground Systems Section. Previously he has been both an engineer and supervisor for JPL's Processor Systems Development Group. Andre has been involved in the development of a number of advanced systems for use in the DSN in the fields of Radio Science, Radio Astronomy, VLBI, and Antenna Arraying. Andre received his BSEE from California State Polytechnic University in 1992.



David N. Fort received a B.A.Sc. in Engineering Physics and M.Sc. in Astronomy from the University of Toronto and an M.Sc. and Ph.D. in Radio Astronomy from the University of Manchester. He joined NRC (Canada) in 1972 and worked on all aspects of VLBI until 1987. He subsequently joined JPL in section 335 and worked on a number of hardware and software projects for the DSN and became supervisor of the Processor Systems development Group for the two years prior to returning to NRC in 2002. Until his retirement in 2010 he worked on

the EVLA Correlator Project. Now a "Guest Worker", he helps out with the EVLA as it becomes fully operational and with occasional questions from JPL.



Charles Goodhart is a senior staff software engineer in the Processor Systems Development Group at JPL. He received a B.S. and M.S. in Applied Mathematics from Caltech. He joined JPL in 1985 to work on the Hypercube Parallel Processor Supercomputer Project and served as the Cognizant Engineer for the Crystalline Operating System (CrOS). He has contributed to a number of high performance computing projects and, most recently has worked on DSN ground systems for radio science and VLBI recording.



Dave Rogstad developed an interest in science early under the influence of his Norwegian immigrant father, and an older brother who allowed Dave to explore his math and science books. After graduating from Caltech with a BS in physics, he went on to earn a PhD in physics, also from Caltech, doing research in radio astronomy. During his 31 years at Caltech and NASA's Jet Propulsion Laboratory (JPL), Dave worked on such high-profile projects as "Star Wars," developing the supercomputers used to simulate national defense scenarios. He also led a technical team that contributed to saving the Galileo Mission to Jupiter. Though Dave stepped down from his leadership role at JPL in 2000 to join the staff of RTB, a science-faith think tank, he still serves as a technical consultant to JPL. Dave has published more than 20 papers on radio astronomy in scientific journals, and also coauthored and edited *Antenna Arraying Techniques in the Deep Space Network*. He lives in Southern California with his wife Diane, and has four grown children and eleven grandchildren.



Robert Navarro received a B.S. in Engineering from Harvey Mudd College in 1986 and a M.S. in Electrical Engineering in 1987. He has been with JPL for more than 19 years. He has worked on DSN ground systems for radio science and VLBI recording as well as correlators and antenna arrays as an engineer and a manager. He is currently the supervisor of the Processor Systems Development Group. His career started with Hewlett Packard working on circuit design and image processing for ink jet printers.

